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(54) Improvements in or relating to cancellers and to echo cancellation methods

(57) An echo canceller for passband data signals includes a pair of real passband filters which generate samples of the echo replica in response to respective streams of rotated data symbol components. As described, the real and imaginary components a_m, b_m of a double sideband quadrature carrier data signal 101 are rotated at 111 by means of a sine and cosine source 109 to generate rotated components a'_m, b'_m which are fed to two (or more) respective transversal filters (fig 2 not shown) constituting the echo canceller 117. Each transversal filter produces an output as function of a single input signal stream as opposed to "cross-coupled" filters which produce a pair of output signals from a pair of input signals, thus allowing simpler computations.

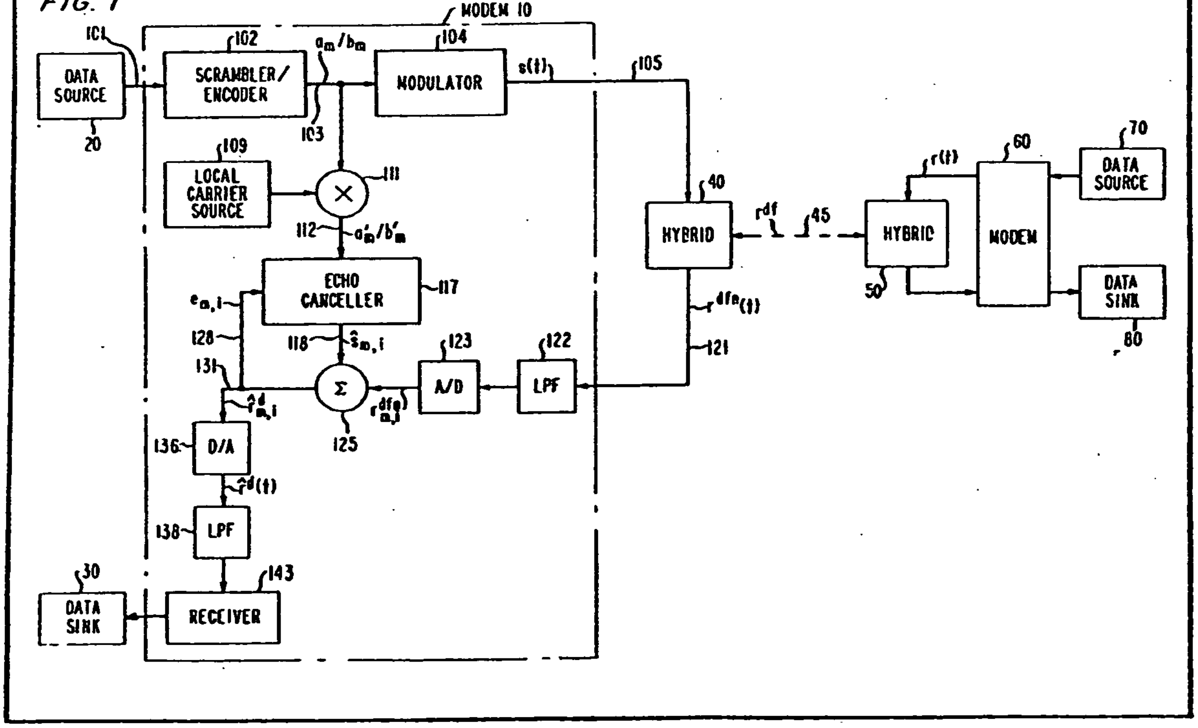

FIG. 1

Certain of the mathematical formulae appearing in the printed specification were submitted after the date of filing, the formulae originally submitted being incapable of being satisfactorily reproduced.

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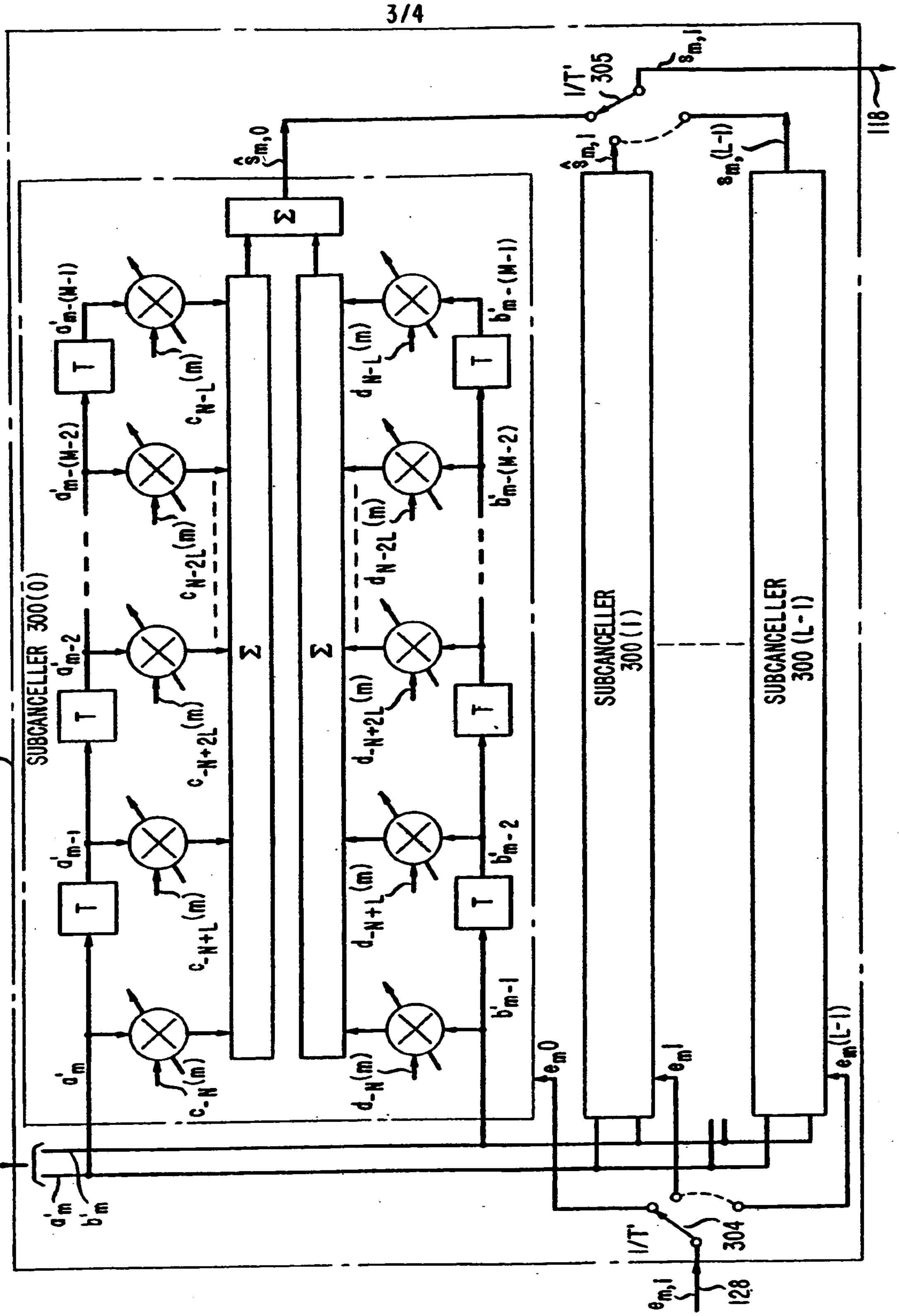
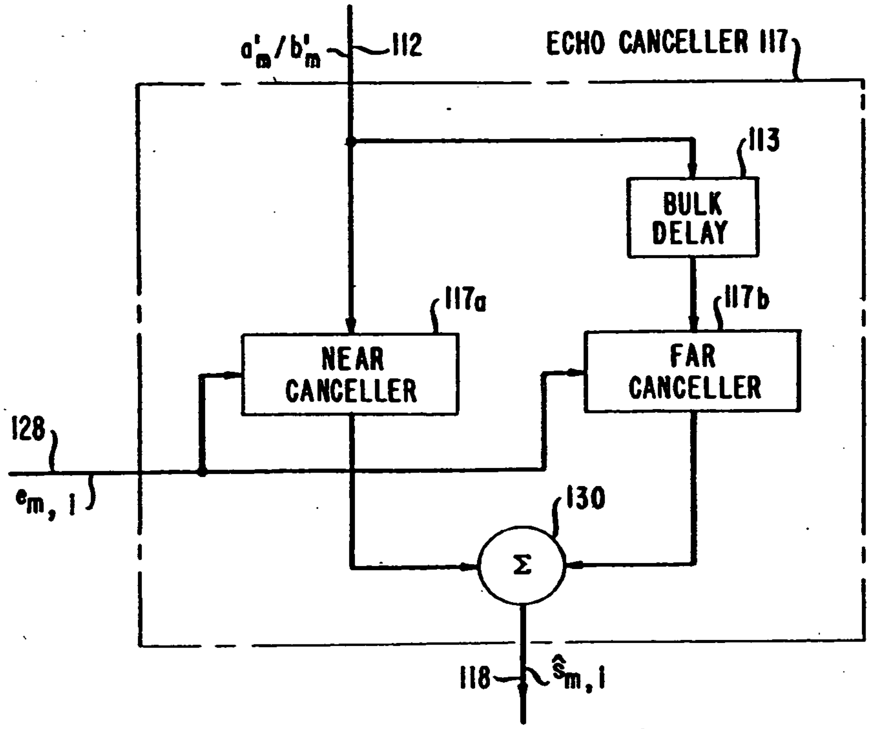


ECHO CANCELLER 117
SUBCANCELLER 300(0)
SUBCANCELLER 300(1)
SUBCANCELLER 300 (L-1)
112
118
128
304
305
1/T'
1/T'
T
T
T
T
T
T
Σ
Σ
Σ

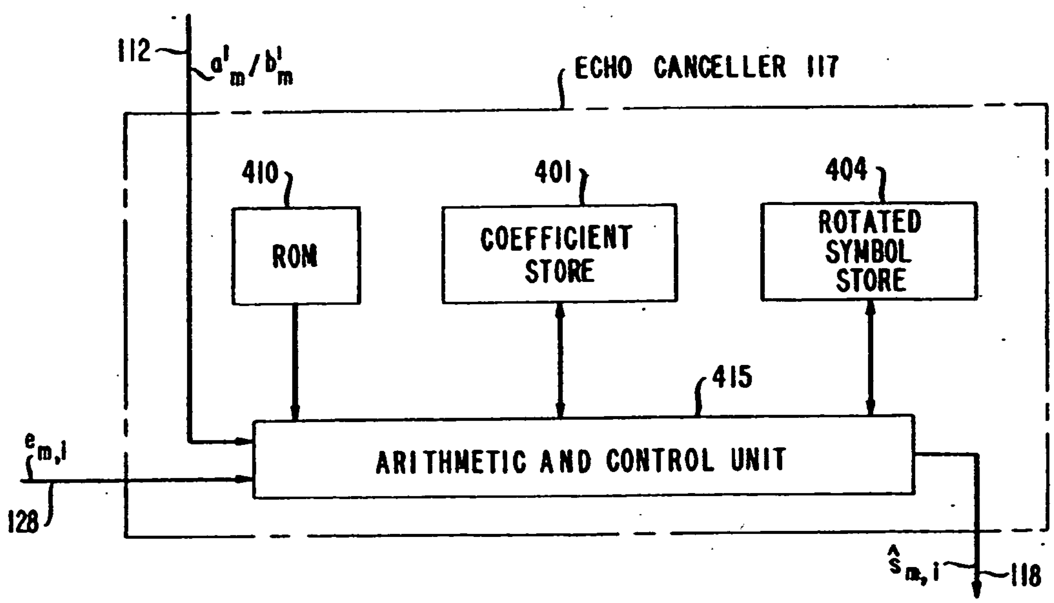
FIG. 3

FIG. 4



a'_m/b'_m
112
ECHO CANCELLER 117
113
BULK DELAY
117a
117b
NEAR CANCELLER
FAR CANCELLER
128
$e_{m,l}$
130
Σ
118
$\hat{s}_{m,l}$

FIG. 5



112
a'_m/b'_m
ECHO CANCELLER 117
410
401
404
ROM
COEFFICIENT STORE
ROTATED SYMBOL STORE
415
ARITHMETIC AND CONTROL UNIT
$e_{m,l}$
128
$\hat{s}_{m,l}$
118

143. The receiver performs such functions as equalization, demodulation, slicing, decoding and descrambling to recover the binary data stream which originated at data source 70. Receiver 143 applies the recovered data stream to data sink 30.

In this embodiment, canceller 117 includes of a pair of real bandpass filters. By "real" filter is meant a filter whose output signal is a function of a single input signal stream. (Prior art echo cancellers for data signals of this type, by contrast, utilize a so-called "cross-coupled", complex filter which provides a pair of output signals each of which is a function of a pair of input signal streams).

In particular, the two real filters of the present illustrative embodiment respectively operate on rotated symbol components a_m' and b_m', of complex rotated symbols $A_m'=A_me^{j\theta}$ where θ is a function of $\omega_c mT$ and, illustratively, is equal to that quantity. (The angle θ might alternatively also include, for example, a frequency offset correction term). The real and imaginary components of the rotated symbols are thus respectively given by

$$a_m'=a_m\cos(\theta)-b_m\sin(\theta)$$

$$b_m'=a_m\sin(\theta)+b_m\cos(\theta)$$

The rotated symbol components are provided to canceller 117 by multiplier 111. The latter's inputs are a) real and imaginary symbol components a_m and b_m, m=0, 1, 2 . . . , received from lead 103 and b) the quantities cos ($\omega_c mT$) and sin ($\omega_c mT$) received from a local carrier source 109. As described in detail hereinbelow, the outputs of the two filters within canceller 117 are combined to form the echo replica samples on lead 118.

The theoretical basis of the invention will now be explained. Assume, as is typical, that the highest frequency component in Nyquist pulse g(t) (Eq. (1)) is less than the carrier frequency, $\omega_c/2\pi$. In that case, the complex signal in brackets in Eq. (1) is an analytic signal Z(t), where

$$Z(t)=s(t)+j\tilde{s}(t)=\sum_m(a_m+jb_m)g(t-mT)e^{j\omega_c t} \quad (2)$$

and where $\tilde{s}(t)$ is the Hilbert transform of s(t). Equation (2) can be rewritten as

$$Z(t) = \sum_m(a_m+jb_m)e^{j\omega_c mT}g(t-mT)e^{j\omega_c(t-mT)} \quad (3)$$

$$= \sum_m (a_m' +jb_m')X(t-mT), \quad (4)$$

where

$$(a_m'+jb_m') = (a_m+jb_m)e^{j\omega_c mT} \quad (5)$$

and

$$X(t)=g(t)e^{j\omega_c t} \quad (6)$$

Assume that the echo channel has an impulse response h(t). The analytic signal corresponding to the echo channel output signal is

$$Z_1(t)=Z(t)*h(t)=\sum_m(a_m'+jb_m')X_1(t-mT) \quad (7)$$

where the asterisk (*) denotes convolution, where

$$X_1(t)=X(t)*h(t) \quad (8)$$

and where $Z_1(t)$ and $X_1(t)$ are analytic signals. The actual signal at the output of the echo channel is the real part of $X_1(t)$, i.e.,

$$s_1(t)=\sum_m[a_m'x_1(t-mT)-b_m'\tilde{x}_1(t-mT)], \quad (9)$$

where $X_1(t)=x_1(t)+j\tilde{x}_1(t)$.

Since the task of canceller 117 is to generate a replica of the echo energy in the received signal (in this embodiment, more precisely, a digital version thereof) Eq. (9) shows that, as previously described, canceller 117 may indeed comprise a pair of real bandpass filters respectively operating on

rotated symbol components a_m' and b_m', m=0, 1, 2 . . ., with the output signals of the two filters being combined. As indicated by Eq. (9), the respective impulse responses of the two filters are $x_1(t)$ and $-\tilde{x}_1(t)$.

In the present illustrative embodiment, the two bandpass filters of canceller 117 are respective digital transversal filters whose tap coefficients are the sampled values $x_1(kT')$ and $-\tilde{x}_1(kT')$, where k=0, ±1, ±2, . . . and where T' is as previously defined. As shown in Fig. 2, the two transversal filters, denoted 210 and 230, may be implemented with respective tapped delay lines. The delay line of filter 210 comprises N delay sections 211. The delay line of filter 230 comprises N delay sections 231. Each delay section provides a delay of T' seconds so that the total (time) span of the delay line is NT' seconds. Since, as previously defined, 1/T'=L/T, the span of the delay line is M=N/L symbol periods. The real (imaginary) rotated symbol components a_m', (b_m', m=0, 1, 2 . . . are applied to filter 210 (230) via switch 206. The latter operates at a rate of L/T=1/T'=9600 Hz. The rotated symbol components are assumed to be present at the switch inputs only momentarily so that the delay lines of filters 210 and 230 are only sparsely filled. That is, only every L^{th} delay line section of filter 210 (230) contains a real (imaginary) rotated symbol component; the intervening (L−1) sections each contain a zero. Thus, at any one time, filter 210 contains the M real rotated symbol components, a_m', a_{m-1}' . . . $a_{m-(M-1)}'$ and filter 230 contains the M imaginary rotated symbol components b_m', b_{m-1}' . . . $b_{m-(M-1)}'$.

Associated with the delay sections 211 (231) of filter 210 (230) are multipliers 212 (232). Each multiplier of each filter multiplies the tap signal presented to it by a respective coefficient. The outputs of multipliers 212 are combined in combiner 215 once every T' seconds. The outputs of multipliers 232 are similarly combined once every T' seconds in combiner 235. The outputs of combiners 215 and 235 are combined in combiner 261. The i^{th} output of combiner 261 associated with the m^{th} baud interval is echo replica sample $\hat{s}_{m,i}$ and it will be appreciated from the foregoing that echo canceller 117 forms each echo replica sample by forming a weighted sum of the rotated real and imaginary data symbol components.

As indicated in Fig. 2, multipliers 212 and 232 are variable. That is, the value of the coefficient by which each multiplier multiplies the tap signal applied to it is time-variable. In particular, each coefficient has a value associated with the m^{th} baud interval. The ensemble of tap coefficients used in filter 210 are denoted $c_0(m)$, $c_1(m)$ . . . $c_{N-1}(m)$. The ensemble of tap coefficients used in filter 230 are denoted $d_0(m)$, $d_1(m)$ . . . $d_{N-1}(m)$. The coefficient values, and thus the filter transfer characteristics, are updated once per baud interval in response to an error signal on lead 128 in such a way that, over time, the echo energy in the echo compensated signal, i.e., the output signal of combiner 125, is minimized. The particular manner in which the coefficient values may be updated in the arrangement of Fig. 2 will not be described herein. Coefficient updating is discussed, however, in connection with the embodiments described below.

The embodiment of Fig. 2, although operative, is inefficient in that L−1 out of every L multiplications is a multiplication by zero. An equivalent, but more efficient, structure is shown in Fig. 3. This structure takes advantage of the fact that, in each baud interval, L different subsets of coefficients multiply the same M rotated symbol components to provide L respective digital echo replica samples. This being so, canceller 117 can comprise L "subcancellers" 300 (i), i=0, 1, . . . (L−1), as shown in Fig. 3. Each subcanceller, in turn, comprises a pair of tapped delay lines whose delay sections each provide a delay T. One delay line of each subcanceller receives the real rotated symbol components a_m', m=0, 1, 2 . . . and the other delay line receives the imaginary rotated symbol components b_m', m=0, 1, 2 . . . .Since the delay sections each provide a delay T, each delay line is filled with rotated symbol components, i.e., there are no zero entries. The coefficients in the i^{th} subcanceller are a first ensemble of coefficients $c_{kL+i}(m)$, k=0, 1 . . . (M−1), and a second ensemble of coefficients $d_{kL+i}(m)$, k=0, 1, 2 . . . (M−1). By way of example, the structure of subcanceller 300(0) is shown explicitly in Fig. 3.

The L echo replica digital samples generated in each baud interval by the L subcancellers are provided on lead 118 via switch 305 and the processing performed within the echo canceller of Fig. 3 to generate them can be expressed as

$$\hat{s}_{m,i} = \sum_{k=0}^{(M-1)} \left[a'_{m-k} c_{kL+i}(m) + b'_{m-k} d_{kL+i}(m)\right],$$

$$i=0,1\ldots(L-1) \qquad (10)$$

Attention is now redirected to Fig. 1. Echo compensated signal sample $\hat{r}^{d}_{m,i}$ contains not only energy derived from the far-end passband data signal but also uncancelled echo energy resulting from differences between echo replica sample $\hat{s}_{m,i}$ and the echo energy in A/D converter 123 output sample $r^{dfn}_{m,i}$. As a consequence, echo compensated signal sample $\hat{r}^{d}_{m,i}$ can be used to form an error signal sample in response to which the coefficient values, and thus the transfer function, of canceller 117 are updated. The error signal sample, which in this embodiment is identical to echo compensated signal sample $\hat{r}^{d}_{m,i}$, is denoted $e_{m,i}$ and is provided to canceller 117 on lead 128. The coefficient used in any particular subcanceller of Fig. 3, should be updated in response to error signal samples which resulted

(A similar expression obtains for cancellation of the near echo with the term $(P_\gamma/P_s)\,\phi^2_{max}=0$, since there is no phase jitter in the near echo). This equation assumes that the canceller operates with infinite precision, which of course is not realistic. In actuality, the best achievable SNR for a given order of digital precision is

$$SNR=\frac{P_s}{(N_nA)(LSB)} \qquad (22)$$

where LSB is the value of the least significant bit in the digital representation used in the echo canceller. Eq. 22 assumes a system with no channel impairments which, of course, is also not realistic. As a matter of practical design, however, Eqs. 21 and 22 can be used to design the echo canceller by choosing the parameters such that the SNR figure yielded by these equations is somewhat larger than that actually desired. In a system which was actually built and tested—a system in which $\alpha_n=2^{-14}$, $\alpha_f=2^{-14}$, $N_n=16$, $N_f=32$, $A=1$, $LSB=2^{-23}$, $\Phi_{max}=10$ degrees ($\pi/36$ radians) peak-to-peak and P_u is negligible—a composite SNR of 21.5 dB was achieved.

Start-up of the echo cancellation system of Fig. 1 can be achieved by first using any of several known techniques to estimate the round trip delay in the far echo channel in order to determine Δ (Eq. 14); setting all of the coefficients to zero; transmitting a random or pseudo-random symbol sequence; and letting the coefficients adapt using α_{opt} (Eq. 13) with $N=N_n+N_f$. Using this start-up technique in the system that was built and tested, an echo canceller start-up time of about 3 seconds was achieved.

An alternative approach to adapting the coefficients in start-up might be to freeze the coefficients associated with cancellation of the far echo (i.e., the coefficients in Eq. 14 for which $k=\Delta$, $(\Delta+1)\ldots(M_f-1)$; let the other, near cancellation, coefficients adapt using α_{opt}; once the level of the near echo reaches that of the far echo (the required time period being determinable experimentally or by calculation during echo canceller design assuming worst case conditions), continue adapting the near cancellation coefficients, but use that value of α_n which provides the desired SNR; when the near echo is 20 dB below the far echo (the time period required for this again being determinable during echo canceller design assuming worst case conditions), begin adapting the far echo cancellation coefficients using α_{fopt}; once the far echo is at the level of the near echo, switch adaptation of the far echo cancellation coefficients to the value of α_f which provides the desired SNR.

Another design consideration is frequency offset. An analysis shows that performance of the echo canceller is deleteriously affected by even moderate amounts of frequency offset. Accordingly, in applications where frequency offset is anticipated, appropriate corrective measures within the modem should be taken. As previously noted, the parameter θ in the expression for a_m' and b_m' may include a frequency offset correction term.

As previously noted, at the heart of the present invention is the recognition that data signal echo replicas can be generated at passband rather than being generated at baseband and then modulated into the passband. The invention thus encompasses not only conventional double sideband-quadrature carrier systems but other passband systems as well. Thus, for example, although in the present illustrative embodiment, transmitted data signal s(t) has the form shown in Eq. 1, a passband, data signal s'(t) of the form

$$s'(t)=Re\left[\sum_m(a_m+jb_m)g(t-mT)e^{j\omega_c(t-mT)}\right]$$

could be transmitted instead. In that case, the echo cancellers should be provided with unrotated symbol components a_m and b_m, $m=0, 1\ldots$ rather than rotated symbol components a_m' and b_m', $m=0, 1, 2\ldots$. The invention is also applicable to such other modulation schemes as amplitude, phase, and differential phase modulation and combinations of same. (QAM is, of course, a combined amplitude and phase modulation method).

It may also be noted that an echo canceller embodying the invention can be implemented using, for example, a) coefficient adaptation algorithms other than those described herein, b) circuitry which operates at least in part in the analog domain, sampled (staircase) domain or other signal domains and c) real (as opposed to complex) data symbols.

Moreover, although the invention is disclosed herein in the context of a canceller which generates echo replica samples at the Nyquist rate, it is equally applicable to cancellers which generate the echo replica samples at the baud rate, such as the arrangement disclosed in U.S. Patent 4,087,654. In such an application of the present invention, L=1.

Moreover, although the invention is illustrated herein in the context of a data transmission system in which each data symbol is two-dimensional and extends over only one baud interval, it is equally applicable to systems in which each symbol has more than two dimensions and/or extends over two or more baud intervals such as the system disclosed in U.S. Patent 4,084,137.

Claims

1. An echo canceller for use with circuitry which transmits a passband signal representing data symbols each having a first component and a second component and which receives a signal which

includes at least a first echo of the transmitted signal, the canceller including real filter means, means for applying rotated versions of the first and second data symbol components to the filter means, means for combining the output of the filter means with the received signal to form an echo compensated signal and means for updating the transfer characteristics of the filter means in dependence upon the echo compensated signal in such a way that, over time, energy in the echo compensated signal derived from the echo is minimized.

2. An echo canceller for use with circuitry which transmits a double sideband-quadrature carrier signal representing a stream of complex values occurring at a rate of 1/T, and which receives a signal which includes at least a first echo of the transmitted signal, the canceller including means for forming at least a first echo replica sample during each of a succession of T second intervals, each echo replica sample being formed by forming a weighted sum of rotated versions of the real and imaginary components of the complex values, and means for combining each of the echo replica samples with a respective sample of the received signal to form a plurality of echo compensated samples.

3. An echo canceller as claimed in claim 2 wherein each weighted sum formed during any particular one of the T second intervals is formed using a respective ensemble of coefficients.

4. An echo canceller as claimed in claim 2 or 3 wherein the rotated versions of the m^{th} of the real and imaginary components are respectively equal to $\{a_m \cos(\theta) - b_m \sin(\theta)\}$ and $\{a_m \sin(\theta) + b_m \cos(\theta)\}$, where a_m and b_m are respectively the real and imaginary components of the m^{th} of the complex values, θ is a predetermined function of the quantity $(\omega_c mT)$, and ω_c is the radian carrier frequency of the transmitted signal.

5. An echo canceller as claimed in claim 2, 3 or 4 including first and second real filters, means for applying the rotated versions of the real and the imaginary components to the first and second filters, respectively, and means for updating the transfer characteristics of the filters in dependence upon the echo compensated samples in such a way that, over time, energy in the echo compensated samples derived from the echo is minimized.

6. An echo canceller as claimed in claim 2 adapted to form L echo replica samples associated with each interval, L being a selected integer, the echo canceller forming the i^{th} of the L echo replica samples associated with the m^{th} interval in accordance with

$$\hat{s}_{m,i} = \sum_{k=0}^{(M-1)} [a'_{m-k} c_{kL+i}(m) + b'_{m-k} d_{kL+i}(m)],$$

$$i=0,1\ldots(L-1) \qquad (10)$$

where M is a selected integer, a_m' is the rotated version of the real component of the m^{th} complex value, b_m' is the rotated version of the imaginary component of the m^{th} complex value, $c_{kL+i}(m)$ is the kL^{th} one of a first ensemble of tap coefficients associated with the i^{th} echo replica sample, and $d_{kL+i}(m)$ is the kL^{th} one of a second ensemble of tap coefficients associated with the i^{th} echo replica sample.

7. An echo canceller as claimed in claim 6 wherein L is selected such that L/T is equal to at least the Nyquist frequency of the received signal.

8. An echo canceller as claimed in claim 6 or 7 wherein

$$a_m' = a_m \cos(\theta) - b_m \sin(\theta)$$

$$b_m' = a_m \sin(\theta) + b_m \cos(\theta)$$

where a_m is the real component of the m^{th} component of the complex value, b_m is the imagninary component of the m^{th} complex value, θ is a predetermined function of the quantity $(\omega_c mT)$, and ω_c is the radian carrier frequency of the transmitted signal.

9. An echo canceller as claimed in claim 6, 7 or 8 wherein the values of the coefficients are determined as a function of the echo compensated samples.

10. An echo canceller as claimed in any one of claims 6 to 9 including means for determining the values of the coefficients in accordance with

$$c_{kL+i}(m+1 = c_{kL+i}(m) + \alpha a'_{m-k} e_{m,i}$$

$$d_{kL+i}(m+1) = d_{kL+i}(m) + \alpha b'_{m-k} e_{m,i}$$

where $e_{m,i}$ is an error signal which is a function of the i^{th} echo compensated signal sample associated with the m^{th} interval, and α is a selected step size.

11. A method of echo cancellation for use where a passband signal representing data symbols each having a first component and a second component is transmitted and a signal is received which includes at least a first echo of the transmitted signal, the method including applying rotated versions of the first and second data symbol components to real filter means, combining the filtered signals with

the received signal to form an echo compensated signal, and updating the filter means transfer characteristics in dependence upon the echo compensated signal in such a way that, over time, energy in the echo compensated signal derived from the echo is minimized.

12. A method of echo cancellation for use where a double sideband-quadrature carrier signal representing a stream of complex values occurring at a rate of $1/T$ is transmitted and a signal is received which includes at least a first echo of the transmitted signal, the method including forming at least a first echo replica sample during each of a succession of T second intervals, each echo replica sample being formed by forming a weighted sum of rotated versions of the real and imaginary components of the complex values, and combining each of the echo replica samples with a respective sample of the received signal to form a plurality of echo compensated samples.

13. A method as claimed in claim 12 wherein each weighted sum formed during any particular one of the T second intervals is formed using a respective ensemble of coefficients.

14. A method as claimed in claim 12 or 13 wherein the rotated versions of the m^{th} of the real and imaginary components are respectively equal to $\{a_m\cos(\theta)-b_m\sin(\theta)\}$ and $\{a_m\sin(\theta)+b_m\cos(\theta)\}$, where a_m and b_m are respectively the real and imaginary components of the m^{th} of the complex values, θ is a predetermined function of the quantity $(\omega_c mT)$, and ω_c is the radian carrier frequency of the transmitted signal.

15. A method as claimed in claim 12, 13 or 14 wherein the rotated versions of the real and imaginary components are applied to first and second filters, respectively, and the transfer characteristics of the filters are updated in dependence upon the echo compensated samples in such a way that, over time, energy in the echo compensated samples derived from the echo is minimized.

16. A method as claimed in claim 12 wherein L echo replica samples associated with each interval are formed, L being a selected integer, and the i^{th} of the L echo replica samples associated with the m^{th} interval is formed in accordance with

$$\hat{s}_{m,i} = \sum_{k=0}^{(M-1)} [a'_{m-k}c_{kL+i}(m) + b'_{m-k}d_{kL+i}(m)],$$

$$i=0,1\ldots(L-1) \qquad (10)$$

where M is a selected integer, a_m' is the rotated version of the real component of the m^{th} complex value, b_m' is the rotated version of the imaginary component of the m^{th} complex value, $c_{kL+i}(m)$ is the kL^{th} one of a first ensemble of tap coefficients associated with the i^{th} echo replica sample, and $d_{kL+i}(m)$ is the kL^{th} one of a second ensemble of tap coefficients associated with the i^{th} echo replica sample.

17. A method as claimed in claim 16 wherein L is selected such that L/T is equal to at least the Nyquist frequency of the received signal.

18. An echo canceller substantially as herein described with reference to Fig. 1, 2, 3, 4 or 5 of the accompanying drawings.

19. A signal transmission system substantially as herein described with reference to Fig. 1, or to Fig. 1 with Fig. 2, 3, 4 or 5 of the accompanying drawing.

20. A method of echo cancellation substantially as herein described with reference to the accompanying drawings.

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